Effects of gender and reach distance on risks of musculoskeletal injuries in an assembly task

L.W.O'Sullivan and T.J.Gallwey

Ergonomics Research Centre, Manufacturing and Operations Engineering,

University of Limerick, Limerick, Ireland

Corresponding author: Leonard O'Sullivan

Tel: + 353 61 202 850

Fax: + 353 61 202 913

E-mail leonard.osullivan@ul.ie

Abstract

This study investigated differences in elbow and shoulder flexion angles in an assembly task. The experiment involved ten subjects on a simulated assembly task that consisted of seventeen task elements. The locations of the components were at three distances from the subjects. Confidence intervals (90%) were estimated and large differences in risk levels were found when data were pooled from both males and females. Between gender comparisons of joint angles revealed that the male elbow angles were smaller than the females, but the male shoulder angles were greater than the females on average. A within-gender analysis found greater change in angles for the female group with an increase in task distance from the body. This was not the case for the males. This was explained with reference to a previous study that related anthropometrics to differences in joint angles. The shoulder was identified as a joint sensitive to small physical changes in the workplace layout that may make a task more awkward to reach. This was not the case for the elbow. Finally, it was noted that both direction of movement and initial hand location, affected final elbow and shoulder joint angles for task elements.

Relevance to Industry

Data is available in the form of anthropometric tables, reach range distances and proposed workstation heights for industry so that differences both between and within genders can be best accommodated for good ergonomic design of workstations. There is a need to supplement this data with information on the variability of induced upper limb joint angles for repetitive assembly tasks within normal reach so as to assist the optimum design of workstations and reduce the likelihood of injuries.

Keywords : Gender, individual differences, postures, reach, risk of injury.

1. INTRODUCTION

Work-related Musculo-Skeletal Disorders (WMSDs) are common in the majority of industrial settings. In the past they tended to be associated mainly with manual handling of heavy loads but many years of effort have reduced these risks so that today they are more often due to highly repetitive light force tasks. Clinical and epidemiological studies have identified four main causative factors i.e. joint angles away from neutral, rate of repetitiveness, force level, and insufficient recovery time. Many industries, for example computer companies, involve considerable amounts of assembly work, which by its nature is very difficult to automate and so there are many manual jobs. Much of the concern has focused on Repetitive Strain Injuries (RSIs) of the wrist. But, although these jobs may involve intensive hand movements, injuries are not isolated to the hand and wrist, as arm movement requires continuous activation of the shoulder girdle and the glenohumeral joint [Winkel and Westgaard, 1992]. Grieco et al. [1998] in addition to wrist injuries, described incidences of shoulder tendinitis, lateral epicondylitis, and tension neck syndrome in repetitive tasks. In a study of an aircraft engine plant, Dimberg [1987] found that 7.4% of workers had lateral epicondylitis. Kim et al. [1998] suggested that cubital tunnel syndrome is the second most common compression neuropathy of the upper extremity, after carpal tunnel syndrome in the wrist. Hence it follows that there is a need to consider the posture of the whole upper limb and shoulder when evaluating these tasks.

Concern is also growing that evaluation methods are too general and do not allow for differences between people, i.e. inter-individual differences. This need was illustrated by Palmerud et al. [1997] who found that an unacceptably high Intra-Muscular Pressure (IMP) of 40 mmHg in the supraspinatus muscle was reached for shoulder flexion between 30^0 and 45^0. The author was reluctant to suggest a specific upper limit for this but rather suggested a range of values (15^0 to 30^0) depending on inter-individual differences. Similarly, Takala and McGlothin [1993] suggested the need for a “fuzzy band” with some thickness when categorising risk levels for WMSDs, so as to accommodate a variety of individuals in the workplace. In this regard, O'Sullivan and Gallwey [1999] found that risks of wrist injury were higher when using actual Range Of Motion data from individuals instead of population averages.

However, in a study of upper limb postures for prehension movements, Desmugret et al. [1998] reported small intra-individual differences. They also reported that the inter-individual differences represented consistent similarities between subjects, and that these were affected by the initial hand location before movement. O'Sullivan and Gallwey [2000] identified considerable differences for elbow and shoulder flexion between subjects for a simulated assembly task. The mean COV (Coefficient Of Variation) was 0.13 for the elbow and 0.58 for the shoulder. They also found that much of the difference between individuals was explained by differences in anthropometry. For example, stature, body mass and elbow-shoulder distance were significantly related ($p<0.05$) to differences in shoulder flexion angles between individuals in over 50% of the task elements analysed.

WMSDs are more common in women than in men [Battenvi et al., 1998; Fieldman, 1998; Johansson, 1994; Silverstein et al., 1986; Zetterberg and Öfverholm, 1999] but yet the special needs of females are not met [WHO, 1999]. The main factors that appear to explain this are differences in strength and anthropometrics, followed by differences in soft tissue properties, e.g. flexibility. In efforts to prevent injuries, males are often assigned manual handling tasks and females light repetitive tasks. The higher exposure of females to repetitive tasks has been suggested to contribute considerably to the higher female injury rate [Battenvi et al., 1998; Hagberg et al. 1995; Silverstein et al. 1986]. Designing workstations that induce least stressful postures is made easier if only one gender operates at it. However, in the present political climate, workstations must be designed for use by both genders. So it is important when designing the workplace to know the extent of between-gender and within-gender differences in upper limb joint angles.

Risk level estimates are based on clinical and epidemiological data from which dose-response relationships between joint angles and loads have been developed. To be applied successfully to actual workplace tasks, such techniques need accurate actual joint angle data to be obtained during the task. Although it is known that these joint angles differ between operators for the same tasks, little has been published so far about the extent or effects of the differences. Similarly, not much has been published on the effect of workplace dimensions on upper limb joint angles.

In many companies somewhat standard designs of workbench are used, often with the aim of providing a large work surface. In such cases, assembly operators of average, or below average, size have considerable difficulty in reaching to some areas and are forced to adopt bad postures. However, to designers lacking expertise in postural issues, these effects may appear to be negligible, and it is necessary to evaluate the magnitudes of increased risk of injury in such cases.

Hence it was decided to collect data on the sources of variation in upper limb and shoulder flexion angles for a particular assembly workplace, and to examine the effects of different reach distances, both between and within genders, on the risks of injury.

2. METHOD

The work reported here formed the initial part of a large investigation into the postural effects of differences in anthropometry. In order to ensure the realism of the workplace, its layout mimicked that at a local company in the electronics assembly business. Although the actual component assembled was different, the actual dimensions and positioning of components was as near as possible that observed in the company. Most of the operators are female but some are male so both have to be accommodated.

Ten student volunteers, five female and five male (mean age 23.5 years, mean stature 1764 mm, SD 113 mm), who were all right handed, participated in the experiment. To ensure product familiarity they assembled domestic 3-pin electrical plugs. Six of the eight plug components were positioned in bins on the table surface (Figure 1). To examine the effects of reach distance, these six parts bins were set on an arc about the fixture of radii 300mm, 350mm and 400mm for near, mid and far test conditions respectively. The remaining two components, Pins 2 and 3, were placed in bins attached to the front of the table, as in the company, and remained the same for each test condition. A fixture was fixed in position to hold the components during assembly. The table surface height was set at 790 mm and the seat height at 600 mm, based on the industrial data. Subjects were positioned on a chair with 25 mm clearance between their abdomen and the bins at the front of the table.

Each plug assembly operation consisted of seventeen elements, and ten plugs were assembled at each of the three bin distances, preceded by five practice assemblies at the start. To avoid problems of simultaneous tasks with naive subjects, the task was performed with the right hand only. The elements are listed in Table 1 in the order of assembly. For clarity, note that all pick elements are numbered odd and place elements even, with the exception of the last element.

A Penny and Giles Biometrics electro-goniometer (model XM 110) was used to measure elbow flexion as the angle of the lower arm relative to a neutral datum i.e. 90^0 included elbow angle. The signals were amplified and passed through a 16-bit analog-digital converter. LabVIEW software (National Instruments Corp., Austin, Texas) and a 330 MHz PC were used to capture the signals from the goniometers. Video-recordings were also made sideways on to the subjects' right with a Panasonic AG455 video camera, and were viewed on screen to estimate shoulder flexion using a manual goniometer.

[Insert Table 1 and Figure 1 beside each other about here]

3. RESULTS

3.1 Angle variation within pooled gender data

As an approximation 5^{th}, 50^{th} and 95^{th} percentile estimates were made for elbow and shoulder flexion angles for the mid distance bins for each element, based on pooled male and female data (Table 2). The Table shows that mean elbow flexion ranged from 19^0 to 77^0 and shoulder flexion was between -8^0 and 82^0 for the 17 task elements (negative means extension). As illustrated in Figure 1, the bins (except element 17) were positioned in pairs. Mean elbow flexion angles were similar for three of the four pairs of Pick elements, whereas for the shoulder there was only one set of similar angles. Even though some of the joint angles were similar between pairs of Pick elements, there were large differences in COV values in some cases. For example, the 50^{th} percentile shoulder flexion values for element 2 and 4 were 36^0 and 35^0 respectively but the COV values were 0.43 and 0.33 respectively.

Drury's Technique [1987] was applied to the percentile estimates for the joint angle data (Table 3). This technique rates postures from 0 to 3 depending on the deviation of the joint from neutral, and the zones represent injury risk levels of negligible, low, moderate, and severe respectively. For all elements except two there was a minimum difference of one zone score between the 5^{th} and 95^{th} percentile for both the elbow and shoulder. But for some elements the difference was two zones, e.g. element 2 shoulder score changed from zone 0 to 2. However for elements 3 and 9 there was no change in the risk level for shoulder flexion.

[Insert Table 2 and Table 3 about here]

3.2 Gender differences in flexion data

Table 4 contains the flexion data for the females and males for each of the three bin distances. The Table also shows the difference between both genders with the males as a percentage of the females. These values indicate that the male elbow angles were on average 14%, 15% and 11% less than the females for the near, mid and far conditions, whereas the male shoulder angles were on average 2%, 29% and 45% greater than the females for the near, mid and far bin distances.

The male/female elbow differences were largest for the furthest bin (element 9) with the mid bin distance inducing the largest difference of all (-32%). For each of the Place elements, the differences in elbow flexion between genders were between -18 and -25 % in most cases. There was also a decrease in the percentage differences for each of the Place elements with an increase in distance. The males had larger elbow flexion for element 1, i.e. 14%, 20% and 35% for near, mid and far. For the remainder of the Pick elements, male elbow flexion was less than female. The least differences were for element 3 followed by 5 and 7. For elements 5 and 7, the percentages ranged between -8 and -11%.

The shoulder differences were affected more by bin distances than the elbow. For the majority of the elements, the difference between genders increased with an increase in bin distance. The values for three of the elements are difficult to interpret as the shoulder angles were close to zero so therefore the percentage differences were very large.

[Insert Table 4 about here]

3.3 Flexion variability within both genders

The COV values in Table 5 describe the variability in flexion within both genders for each element. The mean COV values at the bottom of the table indicate that the values increased with bin distance for the females, but not for the males. Further examination of the data shows that the female values were largely unchanged between Place elements, and also unchanged between distances. However, the female COV values for the elbow and shoulder increased consistently for the Pick elements between distances (except elements 5 and 7). The values for the female shoulder data were generally higher than the elbow, especially for the Place elements. As noted previously, the male elbow and shoulder COV values did not change on average between the near, mid and far conditions. The male elbow COV values tended to be greater than the female, while the male shoulder values were lower than the female values.

[Insert Table 5 about here]

3.4 The effect of reach distance on joint angles

Figure 2 and Figure 3 contain plots of the average elbow and shoulder angles (across both genders) for the near, mid and far bin distances. In Figure 2, the majority of the data points above 50^0 are for Place elements and do not appear to be affected as much by distance as the Pick elements (lower data points). The angle values from Table 4 indicate that the elbow values increased by almost 50% between the near and far distances for both females and males. The elbow data in Table 4 indicate that the differences between the near and far bin distances ranged from 10^0 to 15^0 for both genders for elements 9,11,13 and 15. From Figure 2, two important points are evident regarding the Place elements. Firstly, the values differ for each of the Place elements, and secondly they were affected very little by distance. However, the differences are consistent.

The plot of the average shoulder values (Figure 3), indicate that the joint angles for the Pick elements were affected very little by distance. There is slight variation in angles for the Place elements (data points between 30^0 and 40^0). This is also supported by the data from Table 4, as the angles decreased for the females but very little for the males.

[Insert Figure 2 and Figure 3 about here]

3.5 Variation in joint angles for Place elements

ANOVA was used to test if direction of movement and distance of bins affected the joint angles of the Place elements for both the elbow and shoulder. The flexion data for the Place elements formed the dependent variable for both ANOVAs. The independent variables consisted of direction (4 levels, based on the location of each pair of bins) and distance (3 levels, near, mid and far). Table 6 contains the results of the ANOVAs. They indicate that direction and distance were both significant ($p<0.05$) in explaining differences in joint angles for the Place elements for both the elbow and shoulder. The direction main effect for the elbow angles was highly significant ($p<0.001$). Neither of the two-way interactions was statistically significant.

[Insert Table 6 about here]

4. DISCUSSION

4.1 Angle variation within pooled gender data

Large joint angle confidence intervals were identified for various task elements. In a previous study of shoulder and elbow joint angles, O'Sullivan and Gallwey [2000] found that inter-individual differences in shoulder angles were strongly related to gross body variables such as stature and body mass, while differences in elbow angles were strongly related to trunk dimensions. This may explain the larger variation in shoulder values as the pooled data consisted of male and female values in which there would be reasonably big anthropometric differences.

There were very few similar shoulder joint angles for pairs of Pick elements, while the elbow angles were similar for three of the four pairs. For each pair of bins, one was positioned above the other. The lack of similar shoulder joint angles for each pair of bins indicates that the shoulder was more sensitive to the slight changes in reach distance than the elbow. The shoulder is a lot more complex joint than the elbow and has more degrees of freedom. This may explain the greater variation in shoulder angles when grasping parts from the bottom bins as the jig may have been an obstruction in front of the bins thereby inducing awkward postures.

Large differences in the Drury posture scores occurred for the 90% confidence intervals. These indicate that some of the task elements induced stressful posture deviations for some individuals but induced safe postures for others. This illustrates the extent of variation that exists in pooled gender data, as risk levels based on average joint angle data would either grossly over-estimate or under estimate the potential injury for some individuals.

4.2 Gender differences in joint angle data

At present there is little data that describes physiological and discomfort properties of the elbow in terms of joint angles. Changes in elbow posture can result in large changes in its moment arm and in muscle cross sectional area. Combined with nerve compression for greater elbow flexion [Kim et al. 1998] and lower upper limb strength for females, it is suggested that the large gender differences in elbow flexion, which in this case ranged between 20^0 and 30^0, may explain some female propensity to injury. The opposite is evident for the shoulder angles as the males had joint angles that were on average between 2^0 and 45^0 greater than the females for each of the distances. Firstly, the greater difference in shoulder angles for the males is suspected of being related to gender differences in anthropometrics. Secondly, the extent of the differences (average 45^0 difference for far condition) is quite large and of concern. This illustrates the need for adjustable workplace designs. In this application, raising the table height to a suitable level for the males, may help to reduce the extreme shoulder joint angles and reduce injuries.

4.3 Joint angle variation within genders

Battenvi et al. [1998] suggested that when the increased exposure of females to highly repetitive tasks is controlled for, they are not more susceptible to injuries. However, the results indicate that this was not the case for the simulated assembly task analysed, as there was greater variation within the female elbow joint data, with the values increasing with distance. Further examination of the data indicated that the greatest source of variation was for the Pick elements furthest from the body. These elements were most probably close to the maximum reach of some of the females, but possibly within the reach of the males. This is supported by the greater female COV values for the far condition elements. A similar pattern was noted for the male elbow data, but the shoulder values were not comparable with the female values as they tended to be a lot lower.

4.4 The effect of distance on joint angles

Elbow flexion increased by almost 50% between the near and far distance for both females and males even though the distance changed by only 100 mm. Even though the difference was often only in the region of 15^0 to 20^0 it is important to consider that this may result in substantially greater moment arm values at the shoulder. The increase in elbow angles also demonstrated the importance of suitable task layout. In industry, similar tasks may be designed with little consideration for the specific positions of the bins. However, it has been demonstrated here that the elbow angles increased for Pick elements by up to 50% for only a 100 mm increase in bin arc radius. Shoulder flexion was not affected as much by the distance of the bins, but rather by their configuration, including any obstacles that induced awkward postures. It appears that the shoulder accommodates the movement required for awkward postures due to its large number of degrees of freedom.

4.5 Variation in joint angles for Place elements

Desmurgret et al. [1998] in their study of prehension movements noted that final hand position depended on the initial location of the hand. The significant main effects for both direction and distance in explaining differences in joint angles for the Place elements complements this and demonstrates the effect in an industrial assembly job. The behaviour was readily evident in the data for the Place elements. For example, female elbow flexion ranged by 12^0 and the males by 9^0 between directions, while the female shoulder values ranged by 18^0 and male values by 15^0 between directions for the mid distance bins. Although the differences were small for the elbow in terms of the joint range of motion, the differences may be of concern when combined with detailed joint angle discomfort properties. However, the values for the shoulder were substantial and suggest that the effects of direction on final hand posture may warrant consideration in the evaluation of tasks. Even though distance was highly significant, it is suggested that a lot of the variation between distances, especially for the shoulder was within the female group.

This study only examined elbow and shoulder flexion. While the elbow joint can only accommodate flexion, the shoulder joint is considerably more complex with many degrees of freedom in movement. There is a need to complement this work with a detailed study of the shoulder joint including shoulder abduction. There is also a need to investigate the specific physiological cost of joint angle variations in a controlled laboratory setting for various combinations of forces, repetition rates and upper limb joint angles. This would provide further insight into the epidemiology of upper limb WMSDs and may help explain the predisposition of some individuals to injuries, especially females.

5. CONCLUSIONS

1. There was a lot of variation in the pooled gender joint angle data that resulted in considerable differences in the risks of WMSDs for each element.
2. The male elbow angles were on average less than the females but the male shoulder angles were greater than the females
3. The effect of increasing distance on the differences between genders was greater for the shoulder than the elbow
4. The COV values for the elbow and shoulder increased for the females with an increase in distance but not for the males
5. The shoulder was more sensitive to changes in physical layout than the elbow, especially for awkward Pick tasks
6. A 100mm change in bin arc radius resulted in an increase in elbow flexion of 50%
7. Both direction of movement and initial hand position had a statistically significant effect on the final posture of the elbow and shoulder
8. There is a need for more detailed study including measurement of more planes of movement at the shoulder and at the wrist.

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Table Captions

Table 1
Task elements

Table 2
Percentile estimates and measured COV values for elbow and shoulder flexion angles for pooled male and female data where negative values indicate extension

Table 3
Drury zones for percentile estimates for pooled male and female data at mid distance

Table 4
Average elbow and shoulder flexion (degrees) for task elements for both genders

Table 5
COV values for both female and male elbow and shoulder flexion data

Table 6
ANOVAs for the effects of direction and distance on joint angles for Place elements

Illustration Captions

Fig. 1 View of simulated task with Pick element numbers

Fig. 2 Average elbow joint angles for each   for each task element for near, mid and far distances

Fig. 3 Average shoulder joint angles task element for near, mid and far distances

Tables

Table 1

No	Element
1	Pick base
2	Place base
3	Pick Pin 1
4	Place Pin 1
5	Pick Pin 2
6	Place Pin 2
7	Pick Pin 3
8	Place Pin 3
9	Pick Clip
10	Place Clip
11	Pick Fuse
12	Place Fuse
13	Pick Grip
14	Place Grip
15	Pick Cover
16	Place Cover
17	Place Plug

Table 2

		Elbow Flexion				Shoulder Flexion			
No	Element	5th	50th	95th	COV	5th	50th	95th	COV
1	Pick base	14	25	36	0.30	47	62	76	0.17
2	Place base	55	68	81	0.14	15	36	58	0.43
3	Pick Pin 1	6	24	43	0.56	54	68	82	0.15
4	Place Pin 1	56	71	86	0.16	20	35	51	0.33
5	Pick Pin 2	63	74	86	0.11	-5	9	23	1.10
6	Place Pin 2	49	65	82	0.18	17	34	50	0.36
7	Pick Pin 3	65	75	85	0.10	-20	-8	4	-1.13
8	Place Pin 3	50	68	86	0.20	16	29	43	0.35
9	Pick Clip	9	28	46	0.48	49	65	80	0.18
10	Place Clip	48	66	84	0.21	24	42	61	0.32
11	Pick Fuse	4	19	35	0.58	64	82	100	0.16
12	Place Fuse	39	63	87	0.28	21	40	59	0.35
13	Pick Grip	16	34	53	0.39	12	40	68	0.52
14	Place Grip	59	77	94	0.17	11	30	50	0.47
15	Pick Cover	15	33	52	0.41	46	61	75	0.17
16	Place Cover	53	67	80	0.15	29	45	60	0.26
17	Place Plug	43	59	75	0.20	-12	-1	10	-9.09

Table 3

No	Element	Elbow Flexion 5th	50th	95th	Shoulder Flexion 5th	50th	95th
1	Pick base	0	1	2	1	2	2
2	Place base	2	2	3	0	1	2
3	Pick Pin 1	0	1	3	2	2	2
4	Place Pin 1	2	3	3	1	1	2
5	Pick Pin 2	2	3	3	0	0	1
6	Place Pin 2	2	3	3	0	1	2
7	Pick Pin 3	2	3	3	2	1	0
8	Place Pin 3	2	3	3	0	1	1
9	Pick Clip	0	1	2	2	2	2
10	Place Clip	2	2	3	1	1	2
11	Pick Fuse	0	1	1	2	2	3
12	Place Fuse	2	2	3	1	1	2
13	Pick Grip	1	1	2	0	1	2
14	Place Grip	2	3	3	0	1	2
15	Pick Cover	1	1	2	1	2	2
16	Place Cover	2	2	3	1	1	2
17	Place Plug	2	2	3	1	0	0

Table 4

	No.	Female Flexion Near	Female Flexion Mid	Female Flexion Far	Male Flexion Near	Male Flexion Mid	Male Flexion Far	% Difference ** Near	% Difference ** Mid	% Difference ** Far
Elbow										
1	Pick base	32	23	23	36	27	31	14	20	35
2	Place base	72	73	74	59	59	64	-18	-18	-14
3	Pick Pin 1	32	24	17	31	26	17	-3	7	-1
4	Place Pin 1	76	76	77	60	61	65	-21	-20	-16
5	Pick Pin 2	74	77	78	69	69	71	-8	-10	-10
6	Place Pin 2	71	72	71	55	55	60	-23	-23	-16
7	Pick Pin 3	79	78	79	71	70	73	-10	-11	-8
8	Place Pin 3	74	75	75	58	56	59	-22	-25	-20
9	Pick Clip	39	31	21	32	21	18	-17	-32	-15
10	Place Clip	70	73	72	53	55	59	-25	-25	-18
11	Pick Fuse	28	20	16	26	18	13	-5	-9	-15
12	Place Fuse	72	71	71	49	50	58	-31	-29	-18
13	Pick Grip	48	37	30	39	30	22	-19	-20	-25
14	Place Grip	79	84	82	62	64	67	-22	-23	-18
15	Pick Cover	41	34	24	38	32	24	-9	-5	-2
16	Place Cover	70	71	74	58	59	63	-18	-17	-15
17	Place Plug	67	62	57	61	56	52	-8	-9	-8
							Mean	-14	-15	-11
Shoulder										
1	Pick base	62	60	52	59	64	67	-4	8	29
2	Place base	33	33	26	37	41	42	11	24	65
3	Pick Pin 1	72	66	58	67	72	74	-6	9	28
4	Place Pin 1	33	31	27	43	42	45	31	34	64
5	Pick Pin 2	3	6	4	16	15	16	503*	137*	281*
6	Place Pin 2	36	29	25	39	41	38	8	41	55
7	Pick Pin 3	-7	-8	-7	-1	-8	-3	-91	5	-55
8	Place Pin 3	31	26	22	32	36	36	1	39	62
9	Pick Clip	60	61	57	58	71	74	-3	15	30
10	Place Clip	45	38	32	47	50	50	5	34	59
11	Pick Fuse	82	81	70	76	84	86	-7	4	23
12	Place Fuse	39	34	27	44	51	47	12	50	72
13	Pick Grip	38	29	36	45	58	61	17	102	70
14	Place Grip	23	26	20	38	38	39	65	45	95
15	Pick Cover	61	57	55	57	68	69	-7	20	25
16	Place Cover	48	44	30	44	45	47	-8	2	59
17	Place Plug	-5	-1	-3	6	-1	-1	-230*	122*	-80*
							Mean	2	29	45

*values not included in mean as % differences are not suitable due to large values
** positive % difference indicates greater male values than females and visa versa.

Table 5

No		Female - Elbow Near	Mid	Far	Male - Elbow Near	Mid	Far	Female - Shoulder Near	Mid	Far	Male - Shoulder Near	Mid	Far
1	Base pick	0.30	0.36	0.55	0.19	0.22	0.02	0.21	0.20	0.41	0.14	0.14	0.23
2	Base place	0.09	0.12	0.10	0.12	0.05	0.02	0.35	0.52	0.57	0.30	0.34	0.43
3	Pin 1 pick	0.41	0.55	0.62	0.55	0.67	0.75	0.19	0.17	0.42	0.10	0.14	0.13
4	Pin 1 place	0.10	0.13	0.13	0.16	0.10	0.09	0.43	0.30	0.46	0.41	0.32	0.41
5	Pin 2 pick	0.09	0.08	0.07	0.19	0.16	0.14	4.04	1.94	1.70	0.39	0.28	0.25
6	Pin 2 place	0.13	0.13	0.13	0.19	0.16	0.11	0.31	0.32	0.37	0.31	0.34	0.36
7	Pin 3 pick	0.09	0.05	0.06	0.16	0.14	0.12	-1.13	-1.02	-1.00	-4.33	-1.52	-1.33
8	Pin 3 place	0.13	0.14	0.14	0.20	0.15	0.13	0.32	0.36	0.46	0.26	0.28	0.35
9	Clip pick	0.37	0.45	0.65	0.58	0.52	0.58	0.25	0.21	0.38	0.06	0.11	0.10
10	Clip place	0.15	0.15	0.16	0.24	0.19	0.11	0.34	0.34	0.44	0.24	0.26	0.31
11	Fuse pick	0.60	0.62	0.78	0.81	0.64	0.73	0.17	0.21	0.38	0.08	0.08	0.09
12	Fuse place	0.16	0.17	0.15	0.40	0.39	0.20	0.18	0.24	0.32	0.33	0.34	0.41
13	Grip pick	0.21	0.36	0.50	0.36	0.48	0.44	0.27	0.62	0.37	0.13	0.11	0.03
14	Grip place	0.12	0.12	0.09	0.13	0.11	0.11	0.47	0.62	0.55	0.18	0.20	0.30
15	Cover pick	0.33	0.34	0.53	0.32	0.60	0.44	0.25	0.20	0.39	0.10	0.06	0.03
16	Cover place	0.11	0.11	0.10	0.21	0.14	0.12	0.32	0.33	0.49	0.23	0.16	0.35
17	Plug place	0.17	0.21	0.30	0.17	0.19	0.14	-1.26	-15.6	-1.15	1.01	-4.99	-9.99
	Mean*	0.21	0.24	0.30	0.29	0.29	0.25	0.29	0.33	0.43	0.22	0.21	0.25

* COV values above 1.00 are not included as they exaggerate the mean.

Table 6

	Source	df	Mean Square	F	Sig.
Elbow	Direction	3	372	6.09	0.001***
	Distance	2	186	3.04	0.05*
	Direction * Distance	6	5.6	0.05	NS
	Residual	228	61		
Shoulder	Direction	3	660	4.5	0.05*
	Distance	2	491	3.4	0.05*
	Direction * Distance	6	17	0.11	NS
	Residual	228	144		

Illustrations

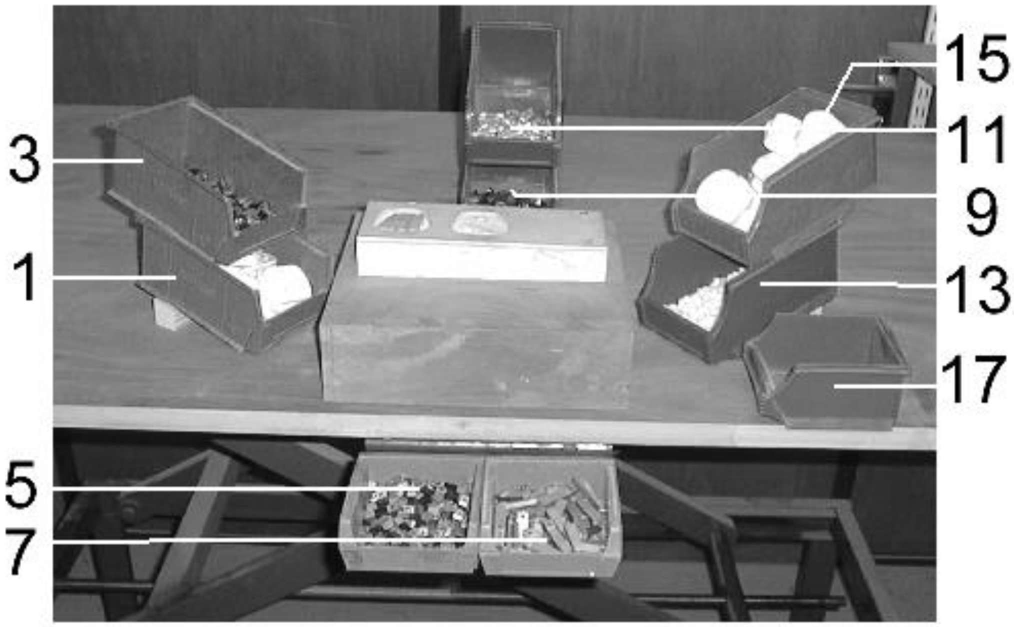

Fig. 1

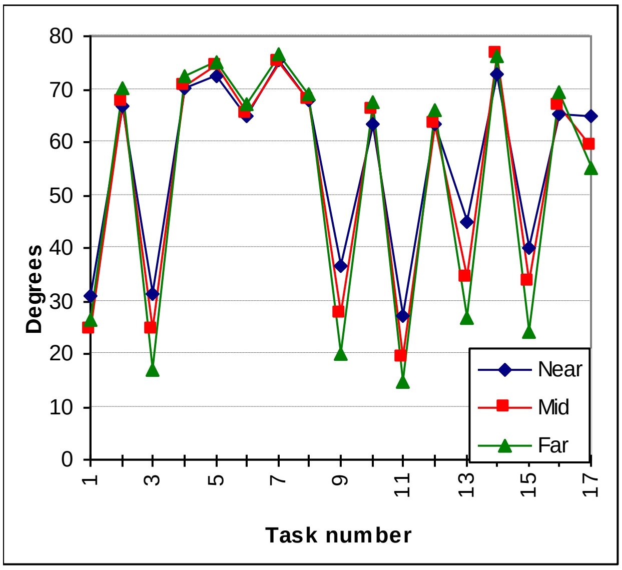

Fig. 2 Average elbow joint angles for each task element for near, mid and far distances

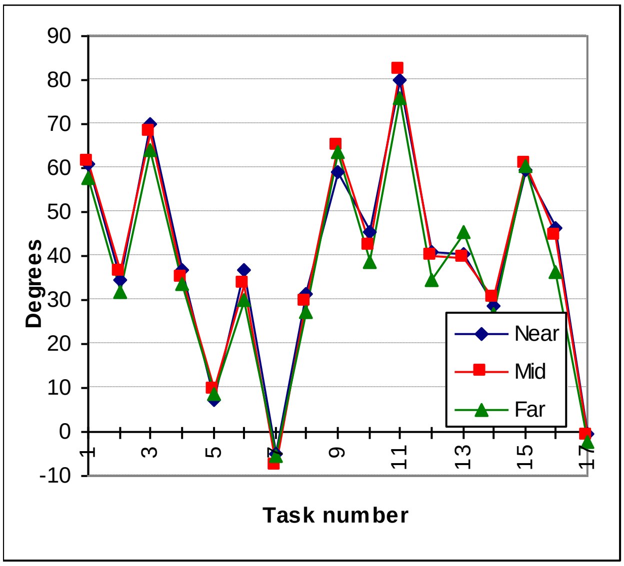

Fig. 3 Average shoulder joint angles for each task element for near, mid and far distances